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Refrigerant-Born NVH Source and TPA Prediction for EV Electric Scroll Compressor

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Abstract

This paper presents a novel methodology for predicting refrigerant-born NVH(Noise, Vibration and Harshness) sources in electric scroll compressor. The approach begins with the development of a comprehensive scroll geometry thermodynamic model capable of simulating refrigerant behavior at thousands of hertz scales. Thermodynamic properties of refrigerant are applied, and the dynamic movement of scroll is modeled by using the scroll geometry parameters . This results in the calculation of the scroll volume, which is subsequently converted into dynamic forces on the scroll surface. The kinematic structure of the electric scroll compressor is then analyzed, and a kinematic model is developed to predict the dynamic force outputs. These dynamic forces serve as inputs for NVH prediction, performed using structural FEM (Finite Element Method) analysis. The model's accuracy is validated using industrial testing data by 1.5% error for 1st order frequency, and it provides a reliable tool for virtual NVH evaluation in EV's refrigerant electric compressor.

Keywords: Electric vehicle, ITMS, Electric Scroll compressor, NVH, TPA

1. Introduction

The global electric vehicle market is rapidly expanding considering global warming and CO2 emission regulation. At the same time, challenging technologies for EV(Electric Vehicle) have been overcomed and optimized. The TMS(Thermal Management System) is one of the essential technologies to overcome for efficient battery and motor operation. Including TMS and climate control, ITMS (Integrated Thermal Management System) has been developed. Recently, many EVs have adopted the heat pump system for the driving range extension. The heat pump uses an electric scroll compressor, which is used for air conditioning and electric device cooling simultaneously.[1-2]

EVs are quieter than internal combustion engine vehicles because the engine, which is the biggest noise source, is excluded. EV ITMS consists of the electric compressor, the coolant electric water pump, the blower, Various electric noise sources. They are transmitted to the interior of the vehicle through various pipes and ducts. (Figure.1) Among them, the electric scroll compressor generates a large pressure change in the refrigerant, which greatly affects efficiency and performance, and at the same time greatly affects NVH. This paper aims to present an EV electric scroll compressor noise prediction methodology for efficient optimization development.

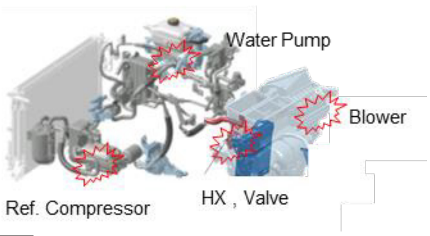

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Figure 1. Various noise sources of EV ITMS

2. Refrigerant Compressor Noise Source Modeling

The industrial data of refrigerant electric compressor should be secured, so this paper used a proposed scroll wraps by the authors (Halm, 1997;Yanagisawa et al, 1990;Wang et al.,2005;Blunier et al., 2006)[4] and the parameters were referred to the produced EV (H-car). This modeling method includes how to identify the parameters as well as how to model the scroll.

2.1. Scroll Compressor Parameter Identifications

The scroll compressor is a compressor designed by Leon Creux in 1905 [3] and consists of a refrigerant compressor composed of a fixed scroll that converts the same scroll shape as the orbiting scroll by 180 degrees. Here PMP(Perfect Meshing Profile) scroll was assumed, and the parameters are identified by SPIN(Scroll Parameter IdentificatioN). [4,6,7,8]

SPIN for short is a Python App dedicated to the automatic identification of scroll compressor geometric parameters. Data points with XY coordinates represensing the inner and outer involutes of the fixed scroll geometry can be imported in the tool. Then the user can tune the different parameters to match the theorical curves with the input data points. The inner and outer involutes can be connected using perfect meshing profile. (Figure.2)

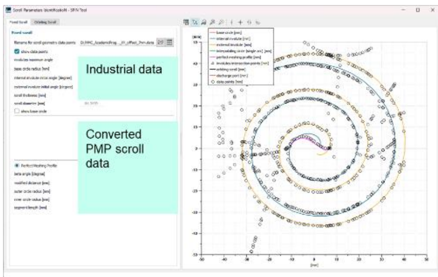


Figure 2. Scroll Parameter Identification Tool (SPIN)

2.2. Compressor Operating Force Modeling

The noise source model of the refrigerant compressor comprises two primary components: a scroll thermodynamic model that predicts refrigerant pressure behavior under various operating conditions, and a body dynamics model that captures the mechanical structure's dynamic response to forces derived from the scroll pressure.

The scroll thermodynamic model encompasses the suction, compression, and discharge processes within the scroll. It subdivides the compressor into discrete control volumes based on discharge stages, enabling the calculation of pressure, flow rate, and temperature within each volume according to its size and operating conditions. This was developed using Simcenter Amesim, a multi-domain simulation platform (Figure 3).

By applying scroll parameters identified experimentally (Section 2.1) and simulating commercial cooling conditions, the model demonstrates that the suction process continues until the closed volume expands to approximately 17 cc. Subsequently, the volume reduces during compression, resulting in increased pressure. During discharge, if the discharge pressure is constrained and the scroll pressure falls below the system pressure, the discharge valve opens, allowing pressure to rise until the suction process recommences. Due to the scroll compressor's inherent design, two separate closed volumes compress simultaneously, collectively matching the compressor's specified displacement of 34 cc. Direct measurement of internal scroll pressure for model validation is challenging; therefore, indirect verification was performed by comparing the model outputs with CCM+ 3D simulation results (Figure 4).

The second component involves a kinetic model of the scroll and rotor assembly to represent power transmission induced by refrigerant pressure on the scroll. This multi-body dynamic model incorporates the orbiting motion of the scroll and includes radial and axial compliance structures that serve as sealing mechanisms to prevent unwanted rotation and enhance performance.[9-13] These features were implemented in Simcenter Amesim using rigid body dynamics and bearing elements capable of representing the 3D geometry (Figure 5). The model accounts for key structural elements such as the eccentric bush rotation center and the pin-and-hole anti-rotational mechanism. Forces acting on the scroll surfaces—including radial, tangential, and axial forces—are transformed into rotational moments based on orthogonal coordinate system components (Fx, Fy, Fz). Additionally, forces from the radial compliance and motor torque, combined with contact forces from the anti-rotation pin-and-hole assembly, are ultimately resolved into bearing forces transmitted to the compressor housing. This comprehensive modeling approach restricts rotational displacement to within 0.1°, ensuring that the orbiting scroll exhibits normal orbiting behavior.

By integrating the scroll thermodynamic model with the multi-body dynamics model of the scroll compressor drive mechanism, a complete noise source model was established. This model captures the transfer of forces generated by both discharge pressure and internal scroll pressures through the bearings, facilitating improved prediction and analysis of refrigerant compressor noise.

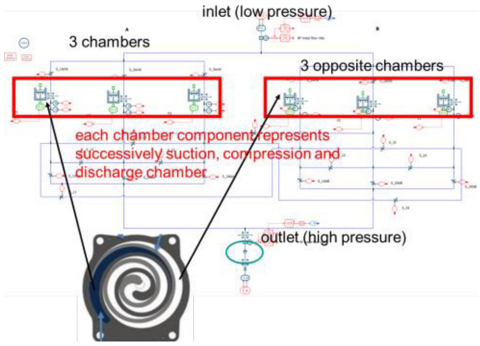
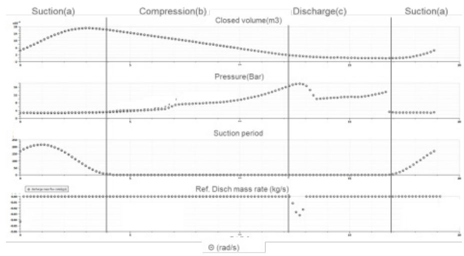
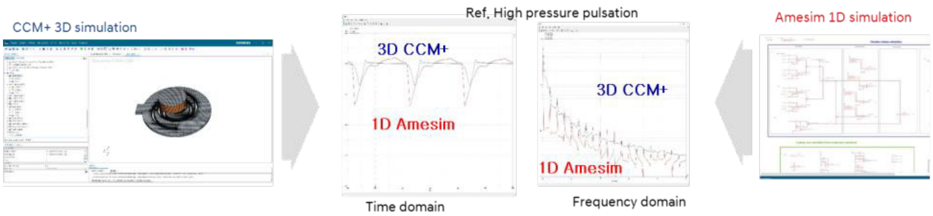


Figure 3. Scroll 1D model for thermodynamic model (Simcenter Amesim used)

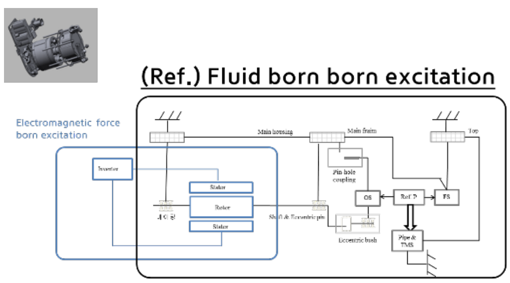


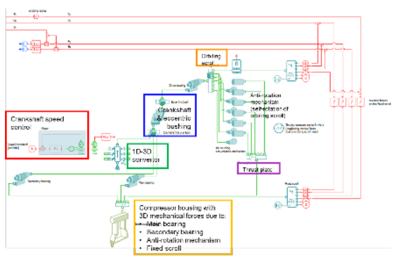
(a) Volume, pressure, and refrigerant discharge behavior analysis



(b) Pressure result of Scroll model (3D results vs. 1D results)

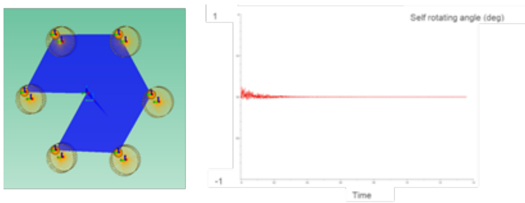
Figure 4. Scroll Volume (SV) Pressure Model Results





(a) Compressor Refrigerant Force Transfer Topology

(b) Dynamics model of Scroll compressor



(c) Scroll orbiting and self-rotation compliance verification

Figure 5. Scroll dynamic modeling

3. Transfer Path Anaysis (TPA) Modeling through TMS and vehicle structure

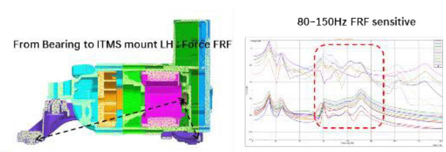
3.1. TPA modeling

In Section 2, a model was developed to predict the force exerted by the scroll compressor driving unit based on the pressure generated by refrigerant flow. A comprehensive noise transfer model for the refrigerant compressor was established by integrating the transmission of force and pressure through the EV TIMS and the vehicle body, ultimately linking these two transfer path analysis to interior noise.

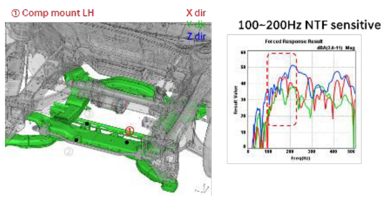
The first step involves predicting the force frequency transfer function (FTF) from the excitation source—described in Section 2.2—to the vehicle body via ITMS. Subsequently, the noise transfer function (NTF), representing the propagation of noise from the mounting points to the vehicle's interior cabin, must be estimated. Due to increasing complexity and mounting points within the ITMS, a multi-source, multi-path transfer analysis approach is required.

In this study, the force transfer functions (ITMS FRFs) were obtained using 3D finite element method (FEM) analysis with SC3D Nastran. The noise transfer functions from mounting points to the vehicle interior (NTFs) were calculated using the H-Car body model. The analysis considered 12 excitation sources at the compressor bearing and high-pressure pipe locations, and six mounting points with three directional components (x, y, z) on the vehicle body, resulting in a total of 216 ITMS FRFs. These FRFs, combined with the mounting points as transfer paths, enabled the calculation of 18 NTFs corresponding to noise responses at the driver's seat.

An automated processing code was developed to integrate the refrigerant compressor noise source, ITMS FRFs, and NTFs, performing Fourier transform-based FFT and frequency response function (FRF) analyses in the frequency domain with automatic A-weighting applied. This facilitated the development of an integrated transfer path analysis (TPA) model, describing the transmission of refrigerant compressor noise through the ITMS into the vehicle interior, as illustrated in Figure 6.



(a) ITMS 3D FEM Model and FRF



(b) ITMS Mounting to Cabin noise NTF

Figure 6. ITMS FRF and Vehicle NFT analysis (FEM)

3.2. Validation of Compressor Operating Noise Prediction Model

The noise prediction methodology for the EV refrigerant compressor was validated through a two-stage process. First, to verify the compressor noise source model, surface vibration measurements of the compressor were conducted under an operating speed of 3,000 rpm during cooling. The experimental results identified a maximum vibration amplitude at the primary excitation frequency of 50 Hz, with similar vibration patterns observed across other frequency bands.

Subsequently, the noise prediction was validated using the integrated transfer path analysis (TPA) model, which simulates the propagation of noise from the refrigerant compressor to the vehicle interior. Interior noise measurements were performed under the same 3,000 rpm cooling condition. At this speed, the predicted noise peak at the fundamental excitation frequency deviated by only 0.5 dB (1.5%) from the measured value, demonstrating high prediction accuracy. However, the maximum noise peak was observed at secondary excitation frequencies, which is likely influenced by the characteristics of the force transfer functions (FTF) and noise transfer functions (NTF).

Table 1. Cabin noise comparison between predicted and tested (1st/2nd Peak, dBA)

Operating condition	Predicted (dBA)	Tested (dBA)
3,000 rpm 1st peak	32.1 (1.5% error)	31.6
3,000 rpm 2nd peak	46.7 (133% error)	20.0

4. TPA Case Studies

This chapter presents various applications of TPA of the compressor noise under key operating conditions relevant to the development of ITMS performance and efficiency for EV. The conditions examined include high-temperature air conditioning, low-temperature heat pump operation, and battery rapid charging.

4.1. Case 1 : High Temperature A/C Operating Conditions

The model utilized H-Car parameters to predict noise variations as the compressor speed increased from 1,000 to 8,000 rpm. The refrigerant compressor noise exhibited nonlinear behavior with respect to the primary excitation frequency peak as the rpm changed. Noise levels increased from 1,000 to 3,000 rpm, decreased slightly at 4,000 rpm, then rose sharply from 5,000 rpm, peaking at 6,000 rpm before experiencing a slight decline thereafter. Analysis of the forces applied to the compressor revealed that bearing forces act as the primary excitation source along the transmission path; therefore, transfer path analysis (TPA) focused on this excitation. Bearing forces increased nearly linearly with rotational speed; however, the forces transmitted to the compressor mounting exhibited nonlinear characteristics. Specifically, the Z-direction force increased rapidly beyond 5,000 rpm, reaching a maximum at 6,000 rpm, directly influencing cabin noise. Furthermore, the force transfer function (FRF) of the integrated thermal management system (ITMS) displayed multiple nonlinear peaks within the frequency range of 80 to 150 Hz, significantly impacting compressor noise. Vehicle evaluations identified this frequency band as a limiting factor for the compressor's operating range due to elevated noise levels. Similarly, the noise transfer function (NTF) from the mounting points to the interior cabin was unfavorable between 80 and 250 Hz. To broaden the compressor's operating range, it is critical to not only reduce the noise source itself but also to improve the FRF and NTF characteristics of the ITMS within the frequency bands corresponding to the major excitation sources (Figure 7a).

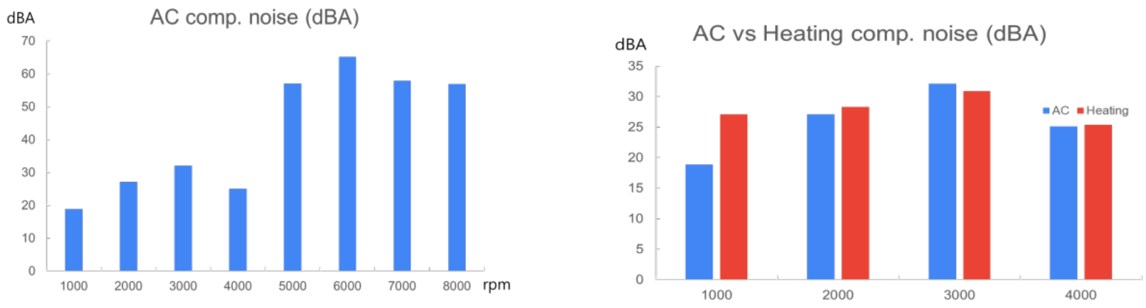
4.2. Case 2 : Low Temperature Heat Pump Operation Conditions

The boundary conditions of the input and output pressures of the refrigerant compressor under low-temperature heat pump conditions differ from those under high-temperature air conditioning (A/C) conditions. Specifically, the high pressure is higher at low temperatures, resulting in approximately 5 to 10% greater excitation power during heat pump operation compared to the refrigerant compressor's excitation source under high-temperature conditions. However, since the transfer path analysis (TPA) model assumes that the force transfer function (FRF) and noise transfer function (NTF) remain unchanged across temperatures, only a 1 dB adjustment reflecting the source difference was applied. Consequently, optimizing the ITMS FRF and NTF in the same manner as performed for the high-temperature A/C operating condition can also effectively reduce noise and expand the operating range of the refrigerant compressor under low-temperature heat pump conditions (Figure 7b).

5. Conclusion

In this study, the operating noise prediction methods of electric vehicle refrigerant compressor was developed and validated like belows :

- Developing an electric scroll compressor parameter identification method
- Development of a High Reliability Compressor Model Integrating a Thermodynamic Model Based on PMP scroll and a Multi-body Dynamics Model of an Electric Scroll Compressor
- Analysis of ITMS FRF and NTF using ITMS and 3D FEM models



(a) AC operating conditions (b) AC vs Heating

Figure 7. Compressor noise case studies by environmental conditions (1st Peak Noise)

Developing an integrated prediction method for TPA analysis using excitation sources and transfer functions

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